THE ROLE OF HDM-4 IN ROAD MANAGEMENT

by

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ABSTRACT

The Highway Development and Management Tools collectively referred to as HDM-4, is the successor to the World Bank Highway Design and Maintenance Standards Model (HDM-III). The scope of the new HDM-4 tools have been broadened considerably beyond traditional project appraisals, to provide a powerful system for the analysis of road management and investment alternatives. In addition to updating the HDM-III technical relationships for vehicle operating costs, and pavement deterioration for flexible and unsealed pavements, new technical relationships have been introduced to model rigid concrete pavement deterioration, accident costs, traffic congestion, energy consumption and environmental effects. The HDM-4 incorporates three dedicated applications tools for project level analysis, road work programming under constrained budgets, and for strategic planning of long term network performance and expenditure needs. It is designed to be used as a decision support tool within a road management system. Standard data import and export facilities are provided for linking HDM-4 to various database management systems. Local adaptation and calibration of HDM-4 models can be achieved by specifying default data sets that represent pavement performance and vehicle resource consumption in the country where the model is being used.

1.   INTRODUCTION

The *Highway Design and Maintenance Standards Model* (HDM-III), developed by the World Bank (*Harral et al, 1987; Watanatada et al, 1988*), has been used for over two decades to combine technical and economic appraisals of road investment projects, and to analyse strategies and standards. An international study has been carried out to extend the scope of the HDM-III model, and to provide a harmonised systems approach to road management, with adaptable and user-friendly software tools. This has resulted in the development of the *Highway Development and Management Tool* (HDM-4) (*Kerali 2000, Odoki and Kerali 2000*). The scope of the HDM-4 tool has been broadened considerably beyond traditional project appraisals, to provide a powerful system for the analysis of road management and investment alternatives. Emphasis was placed on collating and applying existing knowledge, rather than undertaking major new empirical studies, although some limited data collection has been undertaken. Wherever possible, creative new approaches were developed for applying technical knowledge to the management needs of different countries.

1.1   Functions and cycles
When considering the HDM-4 applications, it is convenient to view the highway management process in terms of the following functions (*Robinson et al, 1988*):
- Planning
- Programming

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- Preparation
- Operations

1.1.1   Planning

This involves an analysis of the road system as a whole, typically requiring the preparation of long term, or strategic, planning estimates of expenditure for road development and preservation under various budgetary and economic scenarios. Predictions may be made of expenditure under selected budget heads, and forecasts of highway conditions in terms of key indicators, under a variety of funding levels. The physical highway system is usually characterised at the planning stage by lengths of road, or percentages of the network, in various categories defined by parameters such as road class or hierarchy, traffic flow/capacity, pavement and physical condition. The results of the planning exercise are of most interest to senior policy makers in the road sector, both political and professional. Work will often be undertaken by a planning or economics unit within a road agency.

1.1.2   Programming

This involves the preparation, under budget constraints, of multi-year road works and expenditure programmes in which those sections of the network likely to require maintenance, improvement, or new construction, are identified in a tactical planning exercise. The programming activity produces estimates of expenditure, under different budget heads, for different treatment types and for different years for each road section. Budgets are typically constrained, and a key aspect of programming is to prioritise works to find the best value for money in the case of a constrained budget. Typical applications are the preparation of a budget for an annual or rolling multi-year work programme for a road network, or sub-network. Programming activities are normally undertaken by managerial-level professionals within a road agency, perhaps in a planning or a maintenance department.

1.1.3   Preparation

This is the short-term planning stage where road schemes are packaged for implementation. At this stage, designs are refined and prepared in more detail; bills of quantities and detailed costing are made, together with work instructions and contracts. Typical preparation activities are: the detailed design of an overlay scheme; the detailed design of major works, such as a junction or alignment improvement, lane addition, etc. For these activities, budgets will normally already have been approved. Preparation activities are normally undertaken by relatively junior professional staff and technicians in a technical department of a road agency, and by contracts and procurement staff.

1.1.4   Operations

These activities cover the on-going operation of a road agency. Decisions about the management of operations are made typically on a daily or weekly basis, including the scheduling of work to be carried out, monitoring in terms of labour, equipment and materials, the recording of work completed, and the use of this information for monitoring and control. Activities are normally focused on individual road sections with measurements often being made at a relatively detailed level. Operations are normally managed by sub-professional staff, including works supervisors, technicians, clerks of works, and others.

As the management process moves from *planning* through to *operations*, it will be seen that the changes summarised in Table 1 occur.

Table 1:   Change in management processes

Activity	Time horizon	Responsible Staff	Spatial coverage	Data detail	Mode of computer operation
Planning	Long term (strategic)	Senior management and policy level	Network-wide	Coarse/ summary	Automatic
Programming	Medium term (tactical)	Middle-level professionals	Network or sub-network		
Preparation	Budget year	Junior professionals	Scheme level/ sections		
Operations	Immediate/ very short term	Technicians/ sub-professionals	Scheme level/ sub-sections	Fine/detailed	Interactive

1.2   Management Functions

The highway management process as a whole can, therefore, be considered as a cycle of activities that are undertaken within each of the management functions of *planning, programming, preparation* and *operations*. This is summarised in Table 2 and provides the framework within which HDM-4 needs to be considered.

Table 2:   Role of HDM-4 within the Management Cycle

Management function	Examples of common descriptions	HDM-4 Application
Planning	Strategic analysis system Network planning system Pavement management system	Strategy Analysis
Programming	Programme analysis system Pavement management system Budgeting system	Programme Analysis
Preparation	Project analysis system Pavement management system Bridge management system Pavement/overlay design system Contract procurement system	Project Analysis

2.   HDM-4 ANALYTICAL FRAMEWORK

The HDM-4 analytical framework is based on the concept of pavement life cycle analysis. This is applied to predict the following over the life cycle of a road pavement, which is typically 15 to 40 years (*Kerali, 2000*):

- Road deterioration
- Road work effects
- Road user effects
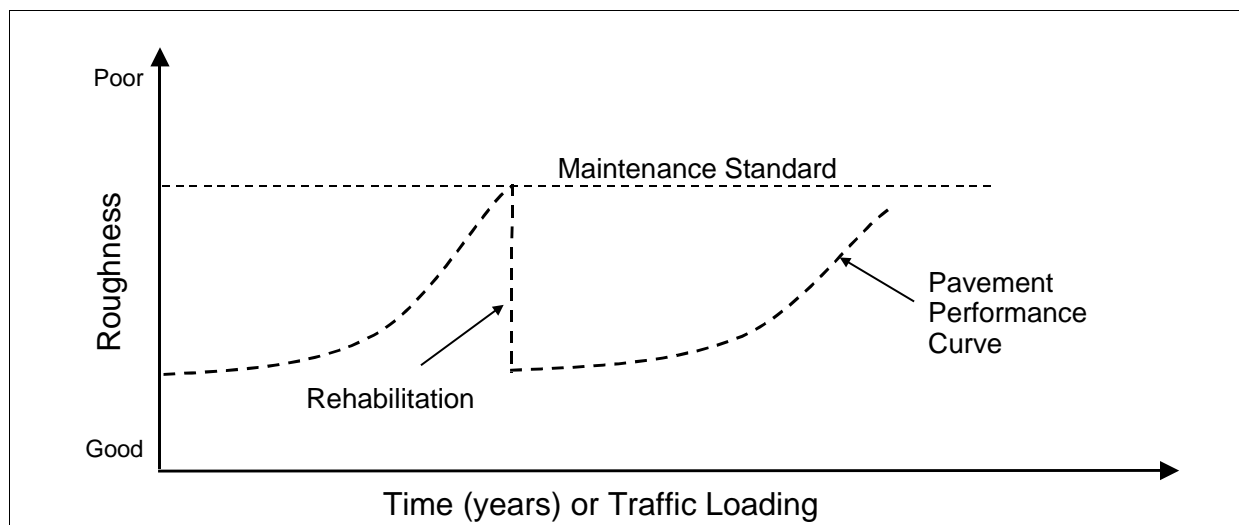- Socio - Economic and Environmental effects

Once constructed, road pavements deteriorate as a consequence of several factors, most notably:

- Traffic loading
- Environmental weathering
- Effect of inadequate drainage systems

The rate of pavement deterioration is directly affected by the standards of maintenance applied to repair defects on the pavement surface such as cracking, ravelling, potholes, etc., or to preserve the structural integrity of the pavement (for example, surface treatments, overlays, etc.), thereby permitting the road to carry traffic in accordance with its design function. The overall long-term condition of road pavements directly depends on the maintenance or improvement standards applied to the road. Figure 1 illustrates the predicted trend in pavement performance represented by the riding quality that is often measured in terms of the international roughness index (IRI). When a maintenance standard is defined, it imposes a limit to the level of deterioration that a pavement is permitted to attain. Consequently, in addition to the capital costs of road construction, the total costs that are incurred by road agencies will depend on the standards of maintenance and improvement applied to road networks. It is essential to note that the accuracy of the predicted pavement performance depends on the extent of calibration applied to adapt the default HDM-4 models to local conditions.

The impacts of the road condition, as well the road design standards, on road users are measured in terms of road user costs, and other social and environmental effects. Road user costs comprise:
- Vehicle operation costs (fuel, tyres, oil, spare parts, vehicle depreciation , utilisation, etc.),
- Costs of travel time - for both passengers and cargo, due to road condition and traffic congestion (*Hoban, 1987*), and
- Costs to the economy of road accidents (i.e., loss of life, injury to road users, damage to vehicles and other roadside objects).

Figure 1:   Concept of Life-cycle analysis in HDM-4

The social and environmental effects comprise vehicle emissions, energy consumption, traffic noise and other welfare benefits to the population served by the roads. Although the social and environmental effects of often difficult to quantify in monetary terms, they can be incorporated within the HDM-4 economic analyses if quantified externally. It should be noted that in HDM-4, road user effects can be calculated for both motorised transport (motorcycles, cars, buses, trucks, etc.) and non-motorised transport (bicycles, human powered tricycles, animal pulled carts, etc.). Figure 2 illustrates the impact of road condition (represented in terms of the IRI) on the costs of different modes of road transport.
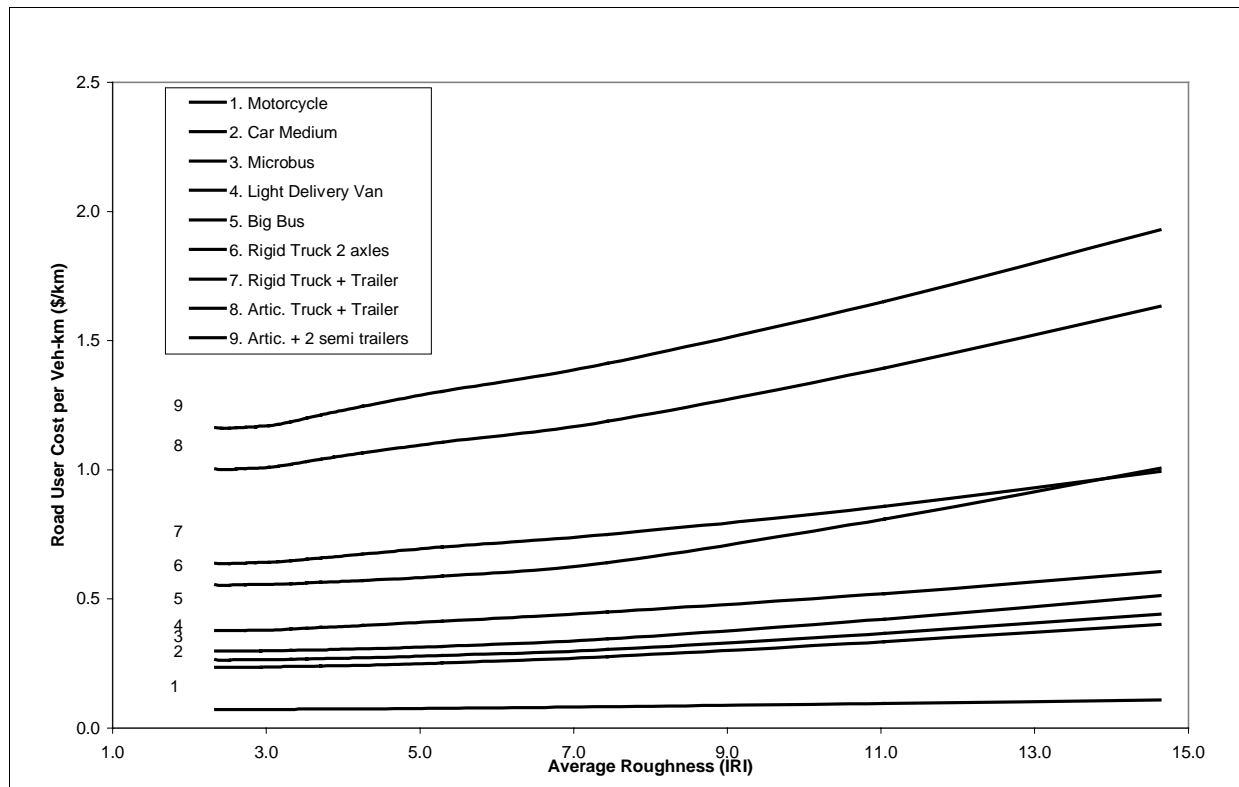
Figure 2:   Effect of Road Condition on Vehicle Operating Costs for Rolling Terrain

Road User Costs in HDM-4 are calculated by predicting physical quantities of resource consumption and then multiplying these quantities by the corresponding user specified unit costs. It is necessary to ensure that the vehicle resource quantities predicted are in keeping with the range of values observed in the area of application.

Economic benefits from road investments are then determined by comparing the total cost streams for various road works and construction alternatives against a base case (without project or do minimum) alternative, usually representing the minimum standard of routine maintenance. HDM-4 is designed to make comparative cost estimates and economic analyses of different investment options. It estimates the costs for a large number of alternatives year-by-year for a user-defined analysis period. All future costs are discounted to the specified base year. In order to make these comparisons, detailed specifications of investment programmes, design standards, and maintenance alternatives are needed, together with unit costs, projected traffic volumes, and environmental conditions.

3.   HDM-4 APPLICATIONS

3.1   Strategy Analysis

The concept of strategic planning of medium to long term road network expenditures requires that a road organisation should consider the requirements of its entire road network asset. Thus, strategy analysis deals with entire networks or sub-networks managed by one road organisation. Examples of road networks include; the main (or trunk) road network, the rural (or feeder) road network, urban (or municipal) road network, etc. Examples of sub-networks include; all motorways (or expressways), all paved (or unpaved roads), different road classes, etc.

In order to predict the medium to long term requirements of an entire road network or sub-network, HDM-4 applies the concept of a road network matrix comprising categories of the road network defined according to the key attributes that most influence pavement performance and road user costs. Although it is possible to model individual road sections in the strategy analysis application, most road administrations will often be responsible for several thousand kilometres of roads, thereby making it cumbersome to individually model each road segment. The road network matrix can be defined by users to represent the most important factors affecting transport costs in the country. A typical road network matrix could be categorised according to the following:

- Traffic volume or loading
- Pavement types
- Pavement condition
- Environment or climatic zones
- Functional classification (if required)

For example, a road network matrix could be modelled using; three traffic categories (high, medium, low), two pavement types (asphalt concrete, surface treatments), and three pavement condition levels (good, fair, poor). In this case, it is assumed that the environment throughout the study area is similar and that the road administration is responsible for one road class (for example, main roads). The resulting road network matrix for this would therefore comprise (3 x 2 x 3 =) 18 representative pavement sections. There is no limit to the number of representative pavement sections that can be used in a strategy analysis. The trade-off is usually between a simple representative road network matrix that would give rather coarse results compared against a detailed road network matrix with several representative sections that could potentially provide more accurate results.

Strategy analysis may be used to analyse a chosen network as a whole, to prepare medium to long range planning estimates of expenditure needs for road development and conservation under different budget scenarios. Estimates are produced of expenditure requirements for medium to long term periods of usually 5-40 years. Typical applications of strategy analysis by road administrations would include:

- Medium to long term forecasts of funding requirements for specified target road maintenance standards (see Figure 3).
- Forecasts of long term road network performance under varying levels of funding (see Figure 4).
- Optimal allocation of funds according to defined budget heads; for example routine maintenance, periodic maintenance and development (capital) budgets (see Figure 5).
- Optimal allocations of funds to sub-networks; for example by functional road class (main, feeder and urban roads, etc.) or by administrative region (see Figure 6).
- Policy studies such as impact of changes to the axle load limit, pavement maintenance standards, energy balance analysis, provision of NMT facilities, sustainable road network size, evaluation of pavement design standards, etc.
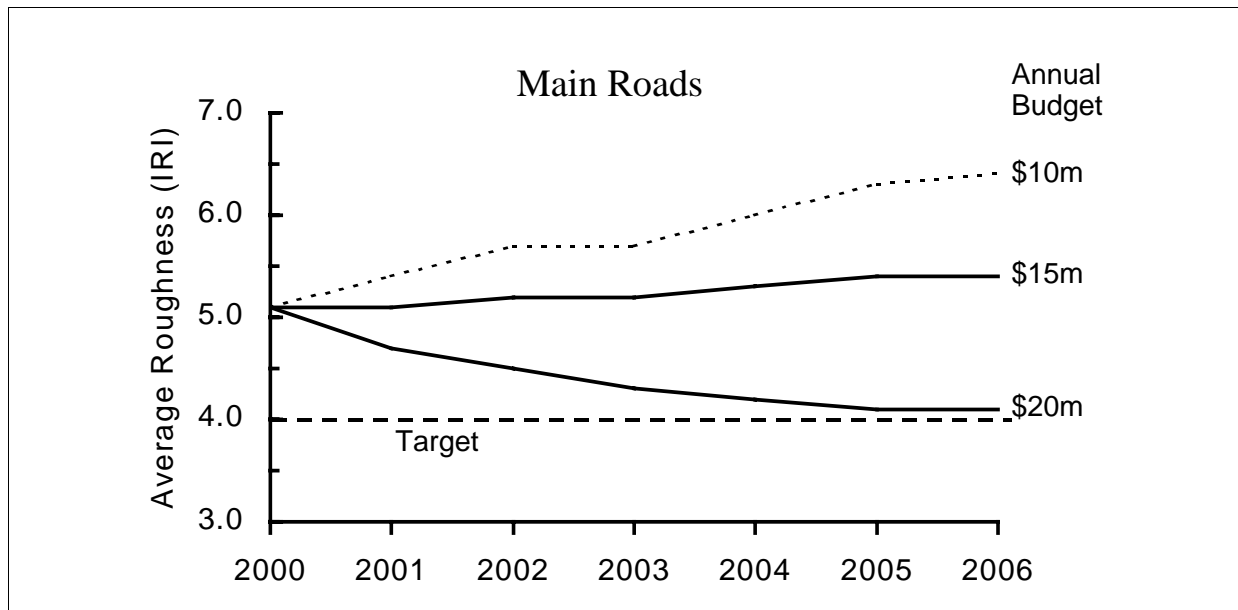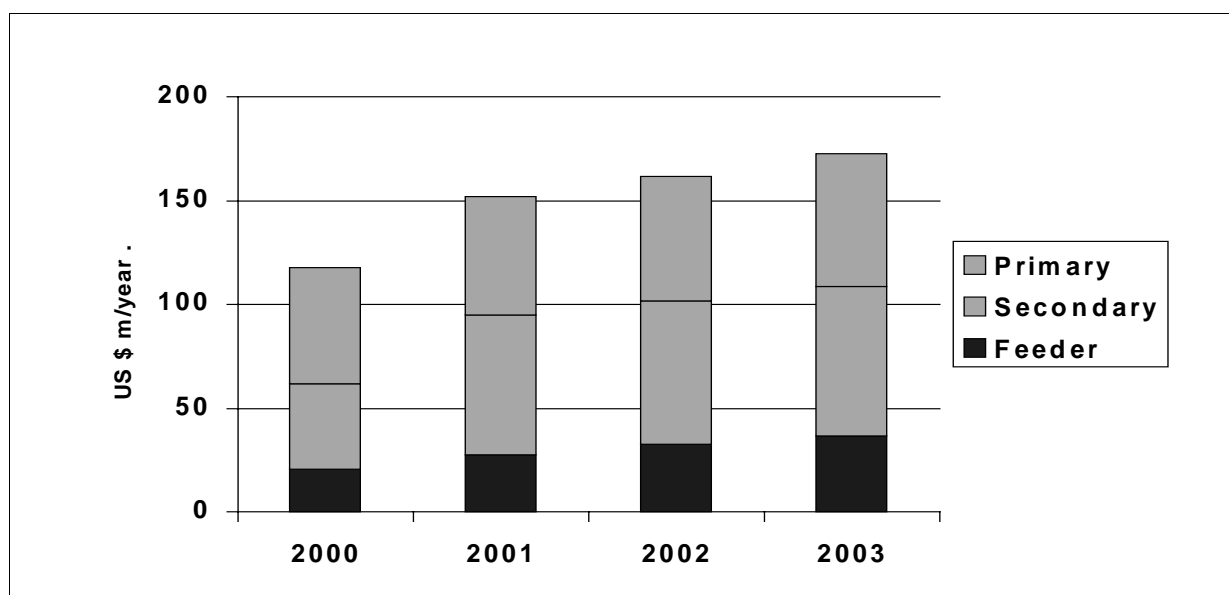
Figure 3: **Effect of funding levels on road network performance**
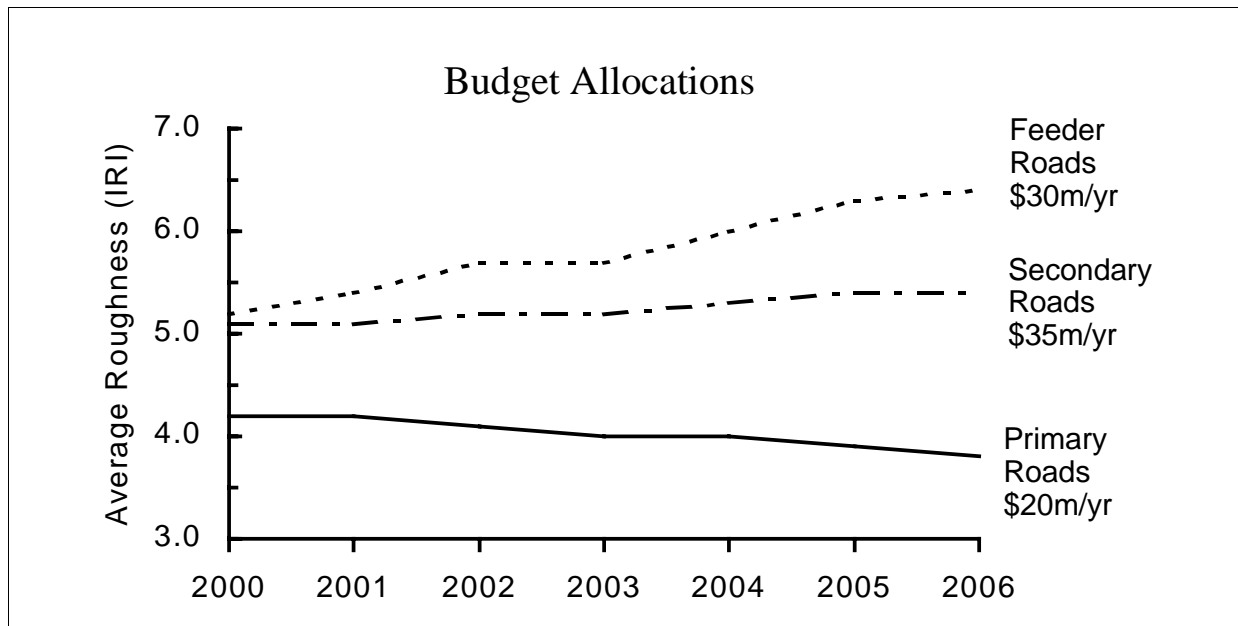
Figure 4: **Effect of budget allocations on sub-network performance**
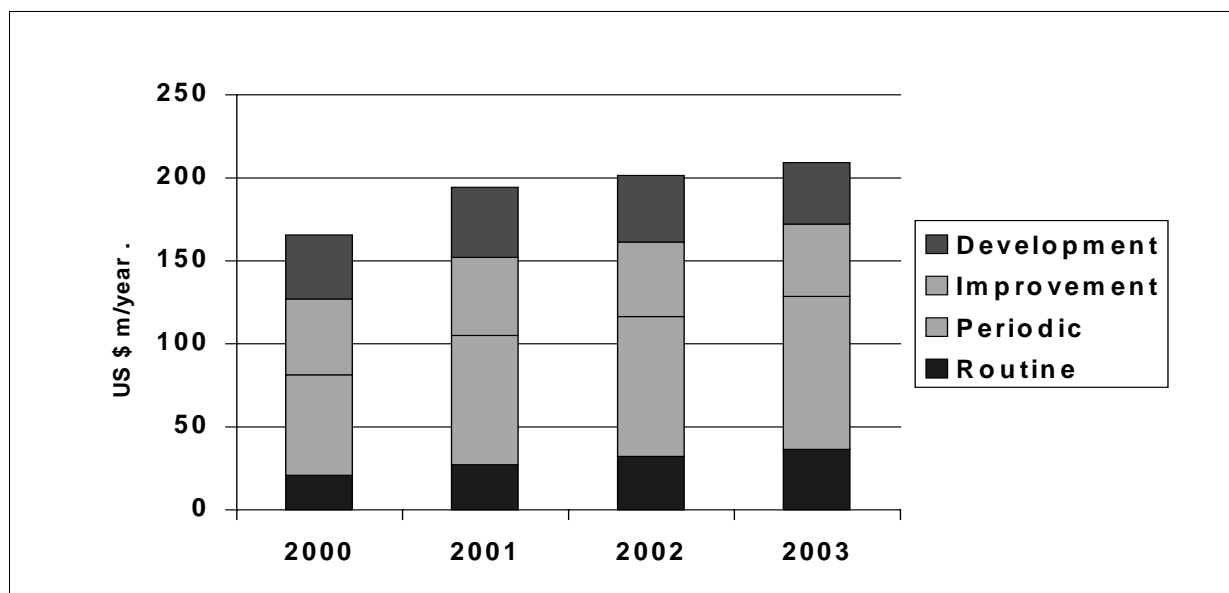
Figure 5:   Optimal budget allocations to sub-heads

Figure 6:   Optimal budget allocations to sub-networks

3.2   Programme analysis

This deals primarily with the prioritisation of a defined long list of candidate road projects into a one-year or multi-year work programme under defined budget constraints. It is essential to note that here, we are dealing with a long list of candidate road projects selected as discrete segments of a road network. The selection criteria will normally depend on the maintenance, improvement or development standards that a road administration may have defined (for example from the output produced by the strategy analysis application). Examples of selection criteria that may be used to identify candidate projects include:

- Periodic maintenance thresholds (for example, reseal pavement surface at 20% damage).
- Improvement thresholds (for example, widen roads with volume/capacity ratio greater than 0.8).

- Development standards (for example, upgrade gravel roads to sealed pavements when the annual average daily traffic exceeds 200 vehicles per day).

The above examples do not imply firm recommendations to be used by road authorities. When all candidate projects have been identified, the HDM-4 programme analysis application can then be used to compare the life cycle costs predicted under the existing regimen of pavement management (that is, the without project case) against the life cycle costs predicted for the periodic maintenance, road improvement or development alternative (that is, with project case). This provides the basis for estimating the economic benefits that would be derived by including each candidate project within the budget timeframe.

It should be noted the main difference between strategy analysis and programme analysis is the way in which road links and sections are physically identified. Programme analysis deals with individual links and sections that are unique physical units identifiable from the road network throughout the analysis. In strategy analysis, the road system essentially loses its individual link and section characteristics by grouping all road segments with similar characteristics into the road network matrix categories.

For both strategy and programme analysis, the problem can be posed as one of seeking that combination of treatment alternatives across a number of sections in the network that optimises an objective function under budget constraint. If, for example, the objective function is to maximise the Net Present Value (NPV), the problem can be defined as:

Select that combination of treatment options for sections that maximises NPV for the whole network subject to the sum of the treatment costs being less than the budget available.

The HDM-4 programme analysis application may be used to prepare a multi-year rolling programme, subject to resource constraints (see Figures 7 and 8). This provides an efficient and robust index for prioritisation purposes.

Indices such as the NPV, economic rate of return (ERR), or predicted pavement condition attributes (for example, road roughness) are not recommended as ranking criteria. The incremental NPV/cost ratio satisfies the objective of maximising economic benefits for each additional unit of expenditure (that is, maximise net benefits for each additional $1 of the available budget invested).

Priority Rank	Road Section	Length (km)	Province or District	Type of Road Work	Scheduled Year	Cost $m	Cumulative S$m
1	N1-2	20.5	2	Resealing	2000	5.4	5.4
2	N4-7	23.5	7	Overlay 40mm	2000	10.9	16.3
3	N2-5	12.5	5	Reconstruct	2000	8.6	24.9
4	R312-1	30	4	Widen 4 lane	2000	31.4	56.3
5	R458-3	36.2	3	Overlay 60mm	2000	16.3	72.6
:	:	:	:	:	:	:	:
1	N4-16	32.1	6	Reconstruct	2001	22.8	22.8
2	R13-23	22.4	4	Overlay 40mm	2001	9.7	32.5
3	N521-5	45.2	2	Widen 4 lane	2001	41.3	73.8
:	:	:	:	:	:	:	:
1	N1-6	30.2	4	Resealing	2002	8.2	8.2
2	N7-9	17.8	3	Overlay 60mm	2002	9.2	17.4
3	F2140-8	56.1	1	Reconstruct	2002	34.9	52.3
:	:	:	:	:	:	:	:

Figure 7:   Sample output from Programme analysis (Format 1)

Priority Rank	Road Section	Length (km)	Province or District	2000 Road Work	Cost $m	2001 Road Work	Cost $m	2002 Road Work	Cost $m	2003 Road Work	Cost $m
1	N1-2	20.5	2	RESEAL	5.4	R.M.	0.185	R.M.	0.185	R.M.	0.185
2	N4-7	23.5	7	OVL40MM	10.9	R.M.	0.212	R.M.	0.212	R.M.	0.212
3	N2-5	12.5	5	RECON	8.6	R.M.	0.113	R.M.	0.113	R.M.	0.113
4	R312-1	30	4	WIDEN-4	31.4	R.M.	0.180	R.M.	0.180	R.M.	0.180
5	R458-3	36.2	3	OVL60MM	16.3	R.M.	0.217	R.M.	0.217	R.M.	0.217
:	:	:	:	:	:	:	:	:	:	:	:
16	N4-16	32.1	6	R.M.	0.289	RECON	22.8	R.M.	0.289	R.M.	0.289
17	R13-23	22.4	4	R.M.	0.134	OVL40MM	9.7	R.M.	0.134	R.M.	0.134
18	N521-5	45.2	2	R.M.	0.407	WIDEN-4	41.3	R.M.	0.407	R.M.	0.407
:	:	:	:	:	:	:	:	:	:	:	:
28	N1-6	30.2	4	R.M.	0.272	R.M.	0.272	RESEAL	8.2	R.M.	0.272
29	N7-9	17.8	3	INLAY	0.240	R.M.	0.200	OVL60MM	9.2	R.M.	0.160
30	F2140-8	56.1	1	PATCH	0.202	R.M.	0.202	RECON	34.9	R.M.	0.168

Note: RM = Routine Maintenance

Figure 8:   Sample output from Programme analysis (Format 2)

3.3   Project analysis

Project analysis is concerned with the following:

Evaluation of one or more road projects or investment options. The application analyses a road link or section with user-selected treatments, with associated costs and benefits, projected annually over the analysis period. Economic indicators are determined for the different investment options.

Project analysis may be used to estimate the economic or engineering viability of road investment projects by considering the following issues:

- The structural performance of road pavements
- Life-cycle predictions of road deterioration, road works effects and costs
- Road user costs and benefits
- Economic comparisons of project alternatives

Typical appraisal projects would include the maintenance and rehabilitation of existing roads, widening or geometric improvement schemes, pavement upgrading and new construction. There are no fundamental changes to the philosophy of the system in this area, but improved road deterioration relationships have been extended to cover a wider range of pavements and the performance of materials in temperate and cold climates. Road user cost relationships include impacts on road safety.

In terms of data requirements, the key difference between the strategy and programme analyses, with that for project analysis, is in the detail at which data is defined. Use is made of the concept of information quality levels (IQL) recommended by the World Bank (*Paterson and Scullion 1990*). Project level analysis data is specified in terms of measured defects (IQL-II), whereas the specification for strategy and programme analyses can be more generic (IQL-III). For example; for project level analysis, road roughness would be specified in terms of the IRI value (m/km); but for strategy and programme analyses, roughness could be specified as good, fair or poor. The relationship between IQL-II and IQL-III level data is user-defined in the HDM Configuration depending on road class, pavement surface type and traffic class.

4. IMPLEMENTING HDM-4 WITHIN A ROAD MANAGEMENT SYSTEM

The HDM-4 model is best seen as the *decision support* component within a complete *road management system*. Figure 9 illustrates the interaction between the components of a road management system. This comprises separate or integrated sub-systems for:

- Data collection
- Database management
- Decision support
- Management information
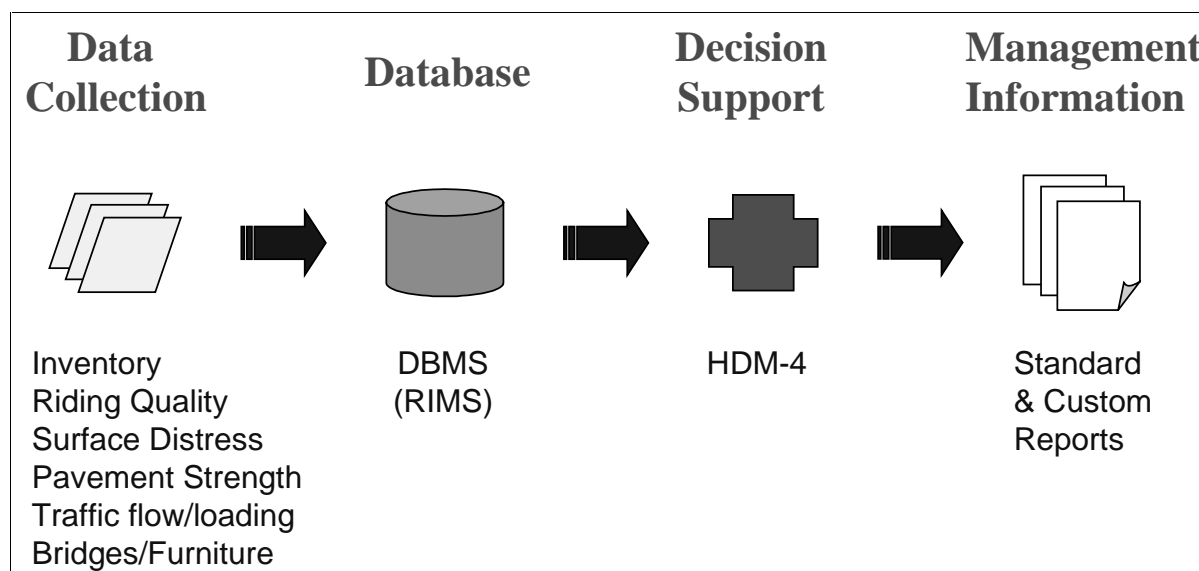
Figure 9:   Components of a Road Management System

4.1   Data Collection
The key aspect about data collection for road management systems is to collect as little as possible that will provide the necessary management information. For purposes of managing pavement maintenance, it is necessary to ensure that the minimum data collected provides information on the road inventory, riding quality, surface distress, pavement strength and traffic characteristics. It is important to note that the measured data items need not correspond to the data requirements of the HDM-4 models. For example, a practical data collection regime could measure pavement condition at IQL III or IV and then utilise a system of default data established either in the database management system, or within HDM-4 to transform these into the IQL I/II data used by the HDM-4 models.

4.2   Database Management System
The HDM-4 system has been intentionally designed to link with any database management system (DBMS). The relational database model, is the most commonly used within road management systems. The method used by HDM-4 to link to other databases is through the use of data import and export files that are created to a predefined format (Wightman et al 2000). The data import into HDM-4 (as well as the export from HDM-4) is organised according to the data objects (road networks, vehicle fleets, maintenance and improvement standards, HDM Configuration). The physical attributes of the selected data objects must be exported to a data exchange file format defined for HDM-4. This permits all data required by HDM-4 to be imported directly from any database. Data transformation rules may need to be implemented for

converting the data held in the external database to the format used by HDM-4. For example, pothole data recorded in the external database in terms of the percentage area of the pavement surface would need to be converted to the equivalent number of standard pothole units (10 litres by volume) required in HDM-4. Similarly, other data required by HDM-4, such as pavement deterioration calibration factors, should be inserted as pre-defined default values according to the type of pavement, road class, and other defined factors. Other data required for the HDM-4 analyses can be directly stored within the HDM-4 internal database. These include data on vehicle fleet characteristics, road maintenance and improvement standards, unit costs and economic analysis parameters (for example, discount rate, analysis period, etc.).

4.3 Decision Support
The key role that HDM-4 would play within a road management system is therefore that of the decision support tool. As such, it is designed to be able to:
- Support all of the functions of Planning, Programming, Preparation and Policy research as described earlier.
- Predict future impacts of funding levels and management policies on the road network performance and on road users.
- Provide reliable predictions of the interactions between the environment, traffic loading, construction standards and maintenance standards on the performance of the road network.
- Assess the impacts of road management policies on the life cycle costs of road pavements.
- Provide a mechanism for investigating optimum investment alternatives in the roads sector.

4.4 Management Information
The purpose of a decision support tool is to provide the key management information that will assist senior policy makers and managers within the roads sector to make good decisions. In addition to these, there will be other management information that should be directly derived from the database. Thus management information may be classed into 3 groups:

- Performance indicators – information that can be used by the public and by the road organisation to measure how well the road network is managed. Such information include predicted network performance trends, average travel speeds and average travel costs over a number of years.
- Operational statistics – information of a quantitative nature that is used mainly within a road organisation to assess budget needs, to measure annual achievements and to make judgements on the effectiveness and efficiency within the organisation.
- Decision criteria – information utilised by middle ranking management and technical professionals to make decision about annual work programmes and to select between project alternatives. These include prioritised lists of road projects and/or the economic indicators of project viability.

5. ADAPTING HDM-4 TO LOCAL CONDITIONS

It is important to note that prior to using HDM-4 for the first time in any country, the system should be configured and calibrated for local use. Since HDM-4 is designed to be used in a wide range of environments, Configuration of HDM-4 provides the facility to customise system operation to reflect the norms that are customary in the environment under study. Default data and calibration coefficients can be defined in a flexible manner to minimise the amount of data

that must be changed for each application of HDM-4. Default values are supplied with HDM-4, but these are all user-definable and facilities are provided to enable this data to be modified. For example, default data can be specified to define traffic ranges such as high, medium and low traffic that may vary according to the system of road classification that is used in the country.

Calibration of HDM-4 is intended to improve the accuracy of predicted pavement performance and vehicle resource consumption. The pavement deterioration models incorporated in HDM-4, were developed from results of large field experiments conducted in several countries. Consequently, the default equations in HDM-4 if used without calibration, would predict pavement performance that may not accurately match that observed on specific road sections. A fundamental assumption made prior to using HDM is that the pavement performance models will be calibrated to reflect the observed rates of pavement deterioration on the roads where the models are applied. The extent of HDM calibration may be defined as follows (*Bennett and Paterson, 2000*):

Level 1:   Application: based on a desk study of available data and engineering experience of pavement performance.

Level 2:   Verification: based on measured pavement condition data collected from a large number of road sections.

Level 3:   Adaptation: Experimental data collection required to monitor the long-term performance of pavements within the study area.

6.   CONCLUSIONS

The HDM-4 system is seen as the international de facto standard decision support tool for road management. In addition to the status of the sponsors or owners of the HDM-4 system, the following reasons are offered for encouraging countries to adopt the HDM-4:

- HDM-4 is based on a well established economic analysis framework.
- The models used are derived from large scale field experiments conducted world-wide.
- It provides a common framework for analysis of road management options.
- It is supported by an international technical team that is behind its development and maintenance.

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